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Project Report: Delivery of Organic Materials to Planets

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Executive Summary
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The success of efforts to find life or life traces on other planets in our Solar System and on other bodies in interstellar space depends on how well we come to understand Earth's prelife environmental conditions and the interplay between early plants, animals, and microorganisms. For example, our identification and understanding of the evolutionary steps and interchanges that ultimately produced Earth's surfaces, seas, and air, on which all living organisms are critically dependent, must be broadened. Knowing the conditions conducive to the development of living organisms on Earth and the evolutionary steps by which nature exploited them is prerequisite to systematic and fruitful searches for life elsewhere in the Universe.

The main goal of research at the Pennsylvania State University Astrobiology Research Center (PSARC) is to increase our understanding of the connection between the environment and Earth's biota, especially during the early stages of evolution. Attainment of this goal will greatly enhance our ability to predict and identify life elsewhere in the Solar System. This work is pursued primarily through multidisciplinary and multidimensional research focused on the following topics:

1. Environment of prebiotic Earth and the origin of life
    1. Experimental approach
    2. Prebiotic chemistry of hydrogen cyanide
2. Biochemistry of archea and bacteria
    1. Enzymes of ancient metabolic pathways
    2. Biochemistry of psychrophilic organisms
    3. Microbe−mineral interactions
3. GEOPULSE: Gene Expression Observations for Planetary Life Study
4. Timescale for the evolution of life on Earth: Molecular evolution approach
5. Evolution of atmospheric oxygen, climate, and biosphere
6. Neoproterozoic variations in carbon and sulfur cycling
7. Causes and consequences of the diversification and extinction of metazoans

Excellent progress has been made in all phases of our research projects. A total of 36 papers related to NAI, including those in press but excluding those submitted, were published by the PSARC members during the third year with the NAI. The PSARC members also gave more than 70 presentations at various international/national scientific meetings.

Progress continues toward understanding the biochemistry of enzymes of metabolic pathways. It has been determined that carbonic anhydrases of the gamma and beta classes evolved distinct mechanisms for the proton transfer step of catalysis. Through genomic analysis of the methanoarchaeon *Methanosacrcina thermophila* , genes with postulated functions have been revealed in novel metabolic pathways.

A wide diversity of viable microorganisms has been found in a more than 200,000 year−old Greenland ice core. The molecular analysis of both extracted DNA and isolates obtained from a community provided a more complete understanding of the diversity than either method alone. Further studies of the survival strategies and growth characteristics of these isolates will be important in understanding the possible existence and survival of organisms elsewhere in the Solar System.

Experiments involving reactions between microbes and minerals show that goethite is essentially insoluble in water under neutral pH. However, in the presence of soil bacteria, lighter iron (Fe) isotopes are preferentially released to solution. Iron isotopic signatures of −1.6 ‰ are measured in dissolved Fe in the presence of *Bacillus* sp. The molybdenum (Mo) release in solution from an Fe−Mo−Ni−silicate glass is enhanced in the presence of *Azotobacter vinelandii*, a nitrogen−fixing soil micro−organism with a molybdenum requirement, but not in the presence of *Bacillus* sp., an aerobic soil micro−organism with specific Mo needs. Molybdenum taken up into asotobacter cells is isotopically light by up to 0.6 ‰. It has also been found that *Anabaena*, a cyanobacterium, extracts phosphate from apatite when grown under ambient conditions; this effect is more rapid in the presence of cells than it is when only in the presence of filtered supernatant solution.

An exciting finding resulted from an investigation of anaerobic methane oxidation: the uncultured archael groups ANME−1 and ANME−2 are involved with the anaerobic oxidation of methane. This result provides important new information regarding the impact of these uncultured organisms on Earth and its history. . Also, *Pyrobaculum aerophilum* extract tungsten from basalt at 100°C, a very significant result that suggests a novel microbial−rock interaction in hydrothermal vents, and a potential geochemical signature of life. Whole−genome content tree analysis has been performed, and the results support Coelomata over the Ecdysozoa for the relationship of animal phyla. This result is important because it suggests a particular way in which an animal evolved.

Phylogenetic analysis of 81 orthologgous protein sequences suggests that, unlike the currently popular view, *Drosophila* is more closely related to humans than to nemotodes, and that the human lineage diverged from *Drosophila*, nematodes, fungi, and plants about 808, 1,024, 1,450, and 1,333 million years ago, respectively.

Using the molecular clock, it was discovered that fungi and land plants appeared much earlier than predicted by the fossil record, possibly affecting the global environment in the late Precambrian. It was also discovered, using genomic analyses and molecular clocks, that there was a likely premitochondrial symbiotic event (2.7 billion years ago) in the origin of eukaryotes, and that cyanobacteria appeared relatively late (2.6 billion years ago) in Earth history.

In a search for the cause of mass extinction, it is suggested that the carbon dioxide level rose to more than 2,300 parts per million (ppm) within 10,000 years of the Cretaceous−Tertiary extinction event. This almost certainly requires an impact into a limestone target, as proposed for the Chicxulub structure. It is also suggested that deep mantle plumes may have carried more oxidized mantle to the surface at the end of the Archean (2.5 billion years ago), reducing the volcanic sink for photosynthetic oxygen and thus promoting the establishment of an oxygen−rich atmosphere. Modeling experiments of the microbial mat suggest that oxygen levels in Archean cyanobacterial mats may have exceeded modern atmospheric saturation values by a factor of 2−3, as modern mats do during afternoon hours. This conclusion is independent of the oxygen or sulfide content of the overlying water.

Based on photochemical modeling, our work suggests that mass−independent sulfur isotope fractionation could have occurred only for the atmospheric O_2 level less than 10^{-5} times present level, and that the atmospheric O_2 rose approximately 2.3 billion years ago. Photochemical modeling suggests that the isotopically light kerogens 2.7 billion years ago may represent the remnants of organic haze produced photochemically within the Archean atmosphere.

Analyses of chemical and isotopic characteristics of organic molecules extracted from Archean marine sediments continue. Results suggest a wide diversity of microbial life in the Late Archean, the distributions and diversity of these compounds varying with depositional environment. Observation of biomarkers in the Late Archean for cyanobacteria is consistent with early and rapid divergences of bacteria, possibly linked to increases in atmospheric oxygen.

The discovery of many new lines of geochemical evidence suggests that the oxygenation of the atmosphere and oceans, the appearance of diverse organisms (including cyanobacteria, methanogens, and sulfate−reducing bacteria) in the oceans and on land, and the development of diverse redox environments, all occurred by about 3.4 billion years ago, which is more than 1 billion years earlier than most geoscientists believe. The results of quantitative modeling of the geochemical cycle of oxygen indicate that the atmospheric oxygen level has been maintained to within ±50 % of the present level since the first appearance of oxygenic photosynthetic organisms by two strong negative feedback mechanisms: one is an increase in the O_2 production flux caused by an increased burial flux of organic carbon with a decrease in pO_2; the other is an increase in the O_2 consumption flux during soil formation with an increase in pO_2.

Research continues on both Precambrian and Phanerozoic paleosols. Recognized variations in soil redox conditions can result in distinct neodymium

(Nd) and strontium (Sr) isotopic signatures in paleosols. The ages of soil formation (2.3 billion years ago) and of metamorphism (1.8 billion years ago) for the Hokkalami paleosols in Finland were determined. It has also been demonstrated that well−ordered dolomite can develop subaerialy within 10^5 years in a noncarbonate substrate, with minimal influence from seawater or atmospheric input from dust or rain. This is relevant for interpretation of the origin of carbonate minerals that could be found in ancient soils on Earth, as well as on Mars or other planetary bodies.

The isotope geochemistry of some Archean marine sedimentary rocks is being studied. A neodymium isotope study of carbonates from the ~2.6 Ga (billion years before present) Hamersley Formation of Western Australia suggests that the ancient oceans were strongly stratified with respect to rare−earth elements (and iron), even before the purported rise in atmospheric oxygen. Samarium−neodymium data from the Hamersley Formation carbonate define an isochron of ~2.1 Ga, significantly younger than the age of deposition (~2.6 Ga). This suggests that rare−earth elements are mobile enough in carbonate to isotopically homogenize over a scale of tens of meters during metamorphism.

Investigations of the sulfur geochemistry of the Neoproterozoic oceans indicate that oceanic anoxia and low terrestrial weathering rates, which prevailed during Neoproterozoic “Snowball” episodes, led to significant perturbations of the sulfur cycle, as evidenced by some of the largest and most rapid isotope variations known for the past 750 million years. These variations have been documented in marine strata from these continents. There might be an important link between the changes in the sulfur cycle to those in the atmospheric contents of methane and oxygen. It is suggested that the first Snowball Earth event might have been caused by increased oxygenation of the atmosphere and oceans, which resulted in an increase in sulfate reduction, a decrease in methane production, and rapid cooling.

Work continues on the causes and consequences of the Ordovician extinction. A drop in pCO_2 to as low as 8 times the present level may not be enough to produce glaciation in the Late Ordovician, unless other factors also change, such as a drop in sea level or a lowering of ocean heat transport. Sample standardization of diversity in Laurentia, suggests that diversity recovered in this area nearly 10 million years earlier than previously thought. This result has implications for ecologic and evolutionary models of recovery from mass extinctions, and also raises the question whether the recovery of global diversity was also much more rapid.

Field Work: Geological field work was conducted in the Abitibi district of Canada and the Lake Superior district of the United States in order to study banded iron formations, red beds, and paleosols formed during the period of 2.7 to 1.8 billion years ago; and in Namibia in order to study the sulfur geochemistry of oceans during the Neoproterozoic Snowball events.

Outreach: Highlights of our outreach activities include: (1) a week−long Workshop on Astrobiology for high school science teachers; (2) a week−long summer program for high school students under the WISE (Women in Science and Engineering) Program; (3) Astrobiology exhibits in a Space Day at Penn State; and (4) participations in the NAI “Ask an Astrobiologist” program.